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The future of fertiliser use

Overview

- Fertilisers are a key component of the food system. They affect food security, both nationally and internationally. The UK currently relies on imported artificial fertilisers for domestic crop production.
- There are economic and environmental concerns arising from the use of artificial fertilisers. These include price volatility and long-term impacts on soil health, air quality, water quality and biodiversity.
- There are opportunities to improve fertiliser production, usage and management that could reduce their impact on the environment.
- Alternatives to artificial fertilisers, such as organic and bio-fertilisers, allow for diversification in fertiliser type, but there are barriers to their uptake.
- Innovations in technologies and practices, such as precision application, improving nutrient uptake and soil health, may lead to more efficient fertiliser use and reduce nutrient losses.
- Diversification and innovation could help to reduce the environmental impact of fertilisers whilst maintaining food security. However, it requires investment, cooperation, an effective evidence base and 'just transition' approaches.

Background

What are fertilisers?

Plants take up nutrients from the soil to grow. When crops are harvested the nutrients required for plant growth are removed from the soil system.[1–3] As a result, most agricultural soils do not contain a sufficient amount of nutrients needed for crops.[4] Fertilisers are applied to replace these nutrients to enhance and support plant growth and development.[2,5]

There are seventeen nutrients known to increase the yield of plants, which are divided into macronutrients and micronutrients.[6] The macronutrients are nitrogen, phosphorus, and potassium (NPK) (Box 1),[4,7,8] although some also classify calcium, magnesium and sulphur as macronutrients.[9,10] The micronutrients are required in very small amounts, and include elements such as iron, copper, manganese, zinc, molybdenum and chlorine.[5,9,10]

Box 1: Macronutrients and artificial fertiliser

- **Nitrogen** - Nitrogen is a major element in fertilisers; it is a key component of chlorophyll and amino acids.[11] Nitrogen from the atmosphere is combined with a natural gas – typically methane – to form ammonia and carbon dioxide.[6,12] This process is known as the Haber-Bosch process. Ammonia produced from this process is combined with carbon dioxide to form urea. Alternatively, nitric acid and ammonia can be combined to produce ammonium nitrate fertilisers.[11,12]

- **Phosphate -** Phosphorus is important in providing energy for the plant.[13] Phosphate-based fertilisers are obtained through mined phosphate rock such as igneous rock deposits (13%) or sedimentary deposits (87%).[6,14] Since phosphate rock is insoluble and thus not available to the plants, ground phosphate rock undergoes a reaction with sulphuric, phosphoric or nitric acid to produce a soluble form of phosphorus.[12]

- **Potassium -** Potassium is critical in plant metabolic processes and cell membrane function.[15] Potassium-based fertilisers (potash) are mined from natural deposits of potassium chloride, which is processed and purified.[12]

What are the types of fertilisers?

There are many different fertiliser types. They differ in physical state, composition and source.[16] The variety of physical forms includes slurries, pellets, granules or powders.[16,17,18] The physical forms used depends on a range of factors including farmer preference.[19] There are two main types of composition: straight fertilisers, which only contains one main nutrient; or compound fertilisers, which contain a mixture of nutrients.[20]

Fertilisers come from a range of manufactured (artificial/synthetic) or natural sources (Table 1).[21,22] As of 2021, conventional practises that tend to use artificial fertilisers accounted for 97% of UK agricultural land uses.[23,24]

Table 1 Definitions

Terms	Definitions
Artificial (synthetic/manufactured) fertilisers	Fertilisers that are manufactured, therefore are considered non-natural.[22] Examples include, nitrogen fertilisers produced via the Haber-Bosch process. These also include fertilisers refined and processed from mined ores, such as potassium from potash ores, or phosphorus from phosphorites.[3,6,25] The term artificial fertilisers is used interchangeably with synthetic fertilisers, inorganic fertilisers and manufactured fertilisers.[21,26]
Organic fertilisers (material)	Fertilisers derived from plants, livestock or humans, such as manure, which contain nitrogen, phosphorus and potassium as well as micronutrients.[26,27]
Biofertilisers	Fertilisers that contain living microorganisms that improve nutrient availability and or use efficiency,[28,29] some particular types of fungi and bacteria are classified as biofertilisers.[28,30]

Food security and fertilisers

Fertilisers increase agricultural productivity and crop yields.[31] As of 2015, more than 50% of the global population was fed with crops grown with artificial fertilisers.[32,33] They make an important contribution to food security.[a,34]

There has been increased demand for fertilisers due to global population growth and changing consumption patterns (PN 589). Data shows a trend of increasing nitrogen fertiliser use with global population growth over recent decades.[35,36] The global population is predicted to grow by approximately 2 billion people by 2050 with food systems[b] needing to meet this demand.[37]

[a] Defra states that food security allows people to access sufficient, safe, sustainable and nutritious food, at affordable prices (PN 556). In the UK, the lack of food security is primarily driven by the lack of affordable nutritious food, as opposed to the scarcity of food (PN 704).

[b] Food Systems are comprised of an assortment of stakeholders that are responsible for; food production, processing, packaging, storage, distribution, consumption, and food waste (PN 702).

However, research suggests that almost half of current global food production relies on practices that are increasing planetary-scale environmental change risks (PN 702).[38] This includes risks arising from changes in the global cycles for nitrogen and phosphorus, with agriculture accounting for an estimated 90% of these inputs into the Earth system.[c,44,40]

Increasing demand could be met through other measures such as reducing losses within the food supply chain (PN 702). Research suggests such changes to food production and consumption could provide sufficient calories for 10 billion people,[44] but may raise just transition issues. Just transition approaches seek to address potential sources of unfairness to provide better outcomes for different groups of people (PN 706), such as the lack of access to nitrogen and phosphate fertilisers in low income countries.[40,45]

The economics of fertiliser use

The global fertiliser price is affected by economic shocks, which can cause price surges (Figure 1). For example, during the financial crisis in 2008, the global price of phosphorus-based fertiliser increased by 850%.[46] In recent years, the price of artificial fertilisers has surged domestically and globally. The price of British nitrogen-based fertilisers (ammonium nitrate) increased by 152% between May 2021 and 2022.[47]

In 2022, CF fertiliser announced the halt in ammonia production as a consequence of the closure of the Billingham plant, a major UK fertiliser plant.[48] Some commentators have attributed this closure to the rapid increase in energy prices affecting the ability to maintain its operations,[48,49] as well as carbon credits.[48,50] There are now policy proposals to apply carbon tariffs to imported fertilisers.[d,51]

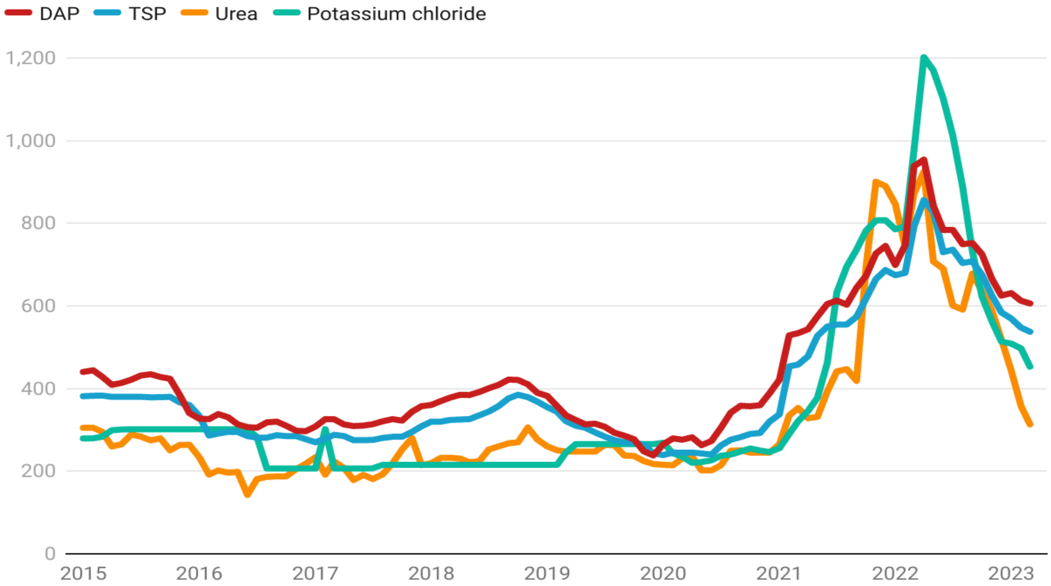
There have been changes to exports from major global producers of fertilisers. For example, of all fertilisers used globally in 2019, Russian exports accounted for 19% of potassium, 15% of nitrogen and 14% of phosphorous.[52] However, sanctions on Russia have since reduced the international supply of fertilisers.[53]

In response to increasing demand and reduced supply, countries that are major global producers, such as China, restricted exports between 2021 and 2022.[54]

[c] Research suggests almost half of current global food production – feeding 3.4 billion people – depends on exceeding four of the nine planetary boundaries, one of which is the human changes to biogeochemical flows of nitrogen and phosphorus (PN 702).[38] Planetary boundaries outline a set of boundaries in which humanity can safely operate. There are nine boundaries; climate change, biodiversity, nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, land use, chemical pollution, and atmospheric aerosol loading.[39] Earth Safety Boundaries (that maintain and enhance the stability and resilience of the Earth system over time) for agricultural nitrogen (N) and phosphorus (P) are estimated to be 61 (35–84) Teragrams of N per year for agricultural nitrogen surplus and 4.5–9.0 Teragrams of P per year for cropland soil phosphorus surplus (Teragram is a metric unit equivalent to 1 million tonnes or a megatonne).[40,41,42,43]

[d] From 2027, carbon intensive goods such as fertiliser that are imported into the UK will be required to pay a carbon border adjustment levy on products from countries that have no/low carbon price, as a means of ensuring comparable pricing.[51]

Figure 1 The increase in diammonium phosphate, triple superphosphate, urea and potassium chloride prices in $ per metric ton



Source: International Food Policy Research Institute[55] - Data from the World Bank

The UK imports most of its artificial fertilisers and the impact of changes in supply and demand has been an acute issue. The cost of importation of artificial fertilisers doubled to £1.2 billion from 2021 to 2022.[56] The costs of artificial fertiliser production could increase further as source materials are exhausted.[57–59] For example:

- Approximately 75% of the remaining global ore resource for phosphorus is located in Morocco,[60] and an estimated 80-95% of phosphate resources have already been mined and dispersed into the environment (PN 477).
- Nitrogen-based fertilisers are produced using fossil fuels as both a feedstock and a source of energy for the reaction.[61,62] Climate change policy may therefore impact on availability and cost.[51]

Addressing the vulnerability of the UK agricultural industry to surges in fertiliser costs would require diversifying sources of production, exploring alternatives to artificial fertiliser and increasing fertiliser efficacy. This may also reduce UK dependency on fertiliser imports and increase food security.

Environmental impacts of fertilisers

Soil health and usage

Soil health[e] underpins many of the ecosystem benefits provided by soil, such as food production, with approximately 98% of human food originating from soil.[64]

Research shows that artificial fertilisers reduce soil health by changing soil structure and chemistry, causing reductions in soil biodiversity (PN 662). The use of heavy machinery to apply artificial and organic fertilisers, in addition to, repeated application of artificial causes soil compaction.[65] This leads to poor aeration and drainage as well as soil erosion.[65,66] Studies suggest some fertilisers may induce soil acidification, which changes soil properties, and can adversely affect plant growth, the soil microbiome[f] and invertebrates (PN 601).[67,68]

Greenhouse gas emissions and air quality

Both organic fertilisers and artificial fertilisers emit greenhouse gases (GHGs), but research indicates that artificial fertiliser results in greater emissions.[69] An estimated two-thirds of the GHG emissions from organic and artificial fertilisers occurs following their application to croplands.[70] However, production of artificial nitrogen-based fertilisers directly emits 450 million tonnes of carbon dioxide per year.[71,72]

Nitrous oxide (N_2O) is a major GHG emitted from the application of nitrogen containing fertilisers, which has a global warming potential[g] over 300 times higher than CO_2[77]. The N_2O is emitted when the microbes break down nitrogen-based fertilisers during the process of denitrification and nitrification in the soil.[72,77]

Research shows that fertilisers affect air quality, impacting human health (PN 691). It is estimated that approximately 11 million tonnes of ammonia is emitted from application of agricultural fertilisers each year.[78] Ammonia from fertilisers and livestock may be converted in the atmosphere to secondary particulate matter, contributing to air pollution.[79] It has been estimated that reducing secondary particulate matter emissions by 50% globally could reduce air pollution and save 250,000 lives annually.[80]

Water quality and biodiversity

Nutrients such as nitrogen and phosphorous from both artificial and organic fertilisers are transported from the soil into lakes and streams via surface water and

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[e] The EFRA Select Committee have stated that the exact definition for soil health is disputed amongst the different stakeholders, however, it generally encompasses the physical, chemical and biological attributes of the soil, as outlined in their 2023 soil health report.[63]

[f] The soil microbiome refers to communities of microbes within the soil, which include bacteria and fungi, archaea, protists and viruses, it is estimated between 4,000 to 50,000 different species of microorganism inhabit per gram of soil (PN 601).

[g] Global warming potential (GWP) measures the relative radiative impact each greenhouse gas has on the climate relative to CO_2 .[73,74] There are different metrics through which this achieved, such as GWP^{100} which examines the GHGs potential over a 100-year time period. An alternative metric is the GWP* which takes into consideration the long and short impacts of GHGs (PN 702).[75,76]

groundwater.[81] The nutrients leave the soil via runoff caused by overapplication, heavy rainfall, seasonality, intense irrigation, type of soil and via soil erosion (PN 661).[81–83]

Once in the water, the nutrients can induce algal blooms in a process known as eutrophication.[84,85] Eutrophication decreases the oxygen concentration, which leads to the death of aquatic life.[84]

Research suggests that 70% of nitrates found in groundwater and surface water can be attributed to agricultural soils in England.[86] Nitrogen and phosphorus are responsible for over 70% of the eutrophication in freshwater and marine environments worldwide.[85]

The long-term effects of fertilisers on freshwater quality are not fully understood as it can take decades for the nitrate to percolate into the groundwater system. This causes a delay between the pollution occurring and the visible impacts and thus result in a delay in mitigation measures and pollution reduction management (PB 40).[87–89]

Deposition of nitrogen (as nitrate, ammonia and nitric acid) from air pollution to the ground can also affect vegetation and soils as well as freshwater systems.[90,91] Excessive nitrogen leads to declines in plant species of high conservation value, and increases in fast-growing species that can exploit the additional nitrogen supply, altering the habitat.[81,92–94]

Trade-offs for higher productivity

Artificial fertilisers can increase productivity of intensive farming systems. They are relatively inexpensive, predictable, stable and nutritionally dense, allowing intensive crop monocultures that achieve high yields.[65,95–99] Artificial fertilisers are also used to improve grass pastureland for feeding livestock directly or through silage and hay production.[100]

Although use of artificial fertilisers affects biodiversity and creates GHG emissions,[101,102] some researchers argue this increased productivity on existing farmland reduces the need to expand the land used for agriculture[h] (PB 42).[104,105] Some researchers suggest that lower productivity agriculture with less use of fertilisers could have lower impacts on wildlife and the environment over a greater land area[i] (PB 42),[105] but would reduce the amount of land available solely for conservation. It could also increase imports of food from countries with greater biodiversity than the UK.[106]

The independent National Food Strategy and some other studies suggest more complex land use models allocating land between high yield farming, wildlife friendly farming and spared natural habitat.[107–110] However, other researchers suggest taking

[h] This is referred to in the academic literature as 'land sparing', which describes the practice of separating intensive agricultural land from biodiversity conservation (PB 42).[103]

[i] This is referred to in the academic literature as 'land sharing', where agricultural land use is integrated with biodiversity conservation (PB 42).

large areas out of production would be a more cost-effective approach to reducing impacts on biodiversity.[110,111]

Legislation, policy, and regulation

Legislation

Legislation on artificial fertilisers has been in place since the 1970's (Table 2). There is legislation covering artificial fertiliser composition, labelling and sampling and analysis procedures.[112] Other legislation is aimed at reducing the impact of fertilisers on the environment.[113]

For instance, the Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018, which is also known as the 'Farming Rules for Water', is a key regulatory tool for nutrient management in England.[114–116] The storing and application of fertilisers is regulated and enforced by the Environment Agency to minimise and prevent diffuse water pollution originating from agricultural practices.[117]

The National Emission Ceiling Regulation 2018 set statutory targets for the UK to reduce the amount of ammonia emissions by 8% by 2020 and 16% by 2030 from a 2005 baseline.[118,j] The Environmental Audit Committee recommended in 2016 that soils should be managed sustainably by 2030 (PN 662).

The 1991 European Nitrate Directive (91/676/EEC) played a key role in reducing organic and artificial fertiliser usage via Nitrate Vulnerable Zones (NVZs). NVZs are agricultural areas that pose a risk of polluting surface or ground water with nitrates.[k,120]

Since EU-exit, the UK countries have developed separate approaches to fertiliser regulation, as a devolved policy area (Table 3). The four UK administrations outlined a fertiliser common framework detailing rules surrounding the import, export, sale or use of fertiliser.[112]

In England the UK Government has pledged to improve land management and the use of fertilisers and to set further water quality targets under the Environment Act 2021.[113] One of the targets is to reduce agricultural nitrogen and phosphorus leaching into the water environment by 40% by 2038 from the levels occurring in 2018.[121] This will require over 85% of farmers to change their current fertiliser practices.[122]

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[j] National Emission Ceilings Regulations (NECR) (Regulations 9 and 10) (S.I. 2018/129) were revoked under the Retained EU Law (Revocation and Reform) Act at the end of 2023. These implement the aspects of the National Emission Ceilings Directive (2016/2284/EC) relating to the National Air Pollution Control Plan (NAPCP). The Government's stated intention was to replace the NAPCP with the air quality targets set in statute through the Environmental Act. The targets for the NECR remain including for ammonia, with the emissions reduction required under the International Convention on Long-Range Transboundary Air Pollution to which the UK is a party (CBP-9600).

[k] NVZs are agricultural areas that pose a risk of polluting surface or ground water with nitrates (NO_3^-) at a concentration greater than 50 mg L^{-1}.[119] NVZ allocated areas have a registration on the amount of organic manure that can be applied by farmers of 170 kg ha^{-1} $year^{-1}$.[119]

Table 2 Overview of key legalisation and regulations

Year	Country	Title
1970	England and Wales	Agriculture Act
1991	England and Wales	The Fertiliser Regulations
1991	EU	Nitrates Directive
1996	Northern Ireland	Fertilisers (Sampling and Analysis)
2000	EU	Water Framework Directive
2006	Northern Ireland	EC Fertilisers
2006	Scotland	EC Fertilisers
2007, 2010 and 2016	England and Wales	Environmental Permitting
2008	Scotland	Action Programme for Nitrate Vulnerable Zones Regulations
2013	Wales	Nitrate Pollution Prevention Regulations 2013
2018	England	Reduction and Prevention of Agricultural Diffuse Pollution Regulations
2018	EU	National Emission Ceiling Regulation
2021	UK	The Environment Act
2021	Wales	Water Resources (Control of Agricultural Pollution) Regulation
2023	Wales	Agriculture Act

Source: Fertilisers common framework, Statute Law Database and Legislation and Guidance[112,123–126]

Policy in England

The UK Government outlined a 25 Year Environment Plan (2018) for England, committing to developing soil metrics and management approaches.[127] The 2022 Food Strategy for England also committed to reducing environmental impacts and GHG emissions of the food system (PN 702).[128]

Table 3 A summary of the approach to NVZs across the UK

England	Since the end of the EU transition period in 2021, England's designated NVZs remain unchanged. Approximately, 55% of land in England is designated as NVZs.[129]
Scotland	Scotland has five designated NVZs, which covers a total of 7,990 km² equating to approximately 10% of land coverage.[130,131]
Wales	Wales replaced the NVZ regulations with Water Resources (Control of Agricultural Pollution) (Wales) Regulations 2021, which applies to all farms (100%) in Wales.[124]
Northern Ireland	Under the Northern Ireland Protocol, the Nitrates Directive was enshrined in NI legislation.[132,112] Action programme under the Nitrates Directive applies to all farms (100%) across Northern Ireland.[132]

Schemes to reduce the impact fertilisers have on the environment have been introduced by the Government[l] such as the Catchment Sensitive Farming Programme, which supports farmers in England to reduce their contribution to water and air pollution.[134] Other policies in England include the Environmental Land Management (ELM) schemes. ELM encompasses three major schemes: [135]

- **Sustainable Farming Incentive (SFI)** provides incentives that reduces artificial fertilisers use or mandate when they are applied.[136]
- **Local Nature Recovery -** provides incentives to reduce the impacts farmed landscape has on water, air quality and biodiversity.[137]
- **Landscape Recovery scheme -** provides support for landowners and managers who undertake changes that lead to long-term biodiversity improvements, improve water quality and help to deliver net zero. [138]

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[l] In addition to government schemes there are industry schemes such as the organic roadmap led by WRAP.[133]

Diversifying artificial fertilisers: opportunities and challenges

Reducing environmental impacts

Diversifying to renewable feedstocks

Hydrogen and nitrogen are required to make ammonia. The predominant way of obtaining the hydrogen is via fossil fuels,[139] which contributes to 90% of the carbon emissions in the production process.[140]

Several methods have been developed to reduce the use of non-renewable feedstocks, including:[139,140]

- Hydrogen for ammonia can be obtained from the electrolysis of water,[139] using electricity from renewable technologies, such as wind and solar.[139,141] It has been estimated that replacing current ammonia production with this process would require 233.6 million tonnes a year of water, which may be challenging in areas with limited water resources, although an electrolysis method using seawater has been developed.[,139,142]
- Plasma-assisted[m] ammonia synthesis combines the nitrogen in the air with water to form ammonia.[144] Less energy intensive processes are being developed to produce hydrogen, such as using water microdroplets.[145]
- Plasma could also be used to fix nitrogen from the air into materials such as slurry.[146]
- Renewable feedstocks such as sewage could be processed to produce macronutrients. For instance, phosphate can be obtained from struvite[n] recovered from sewage treatment plants.[147]

However, all alternative production approaches for fertiliser feedstocks have development challenges, including a need for better understanding of environmental impacts, and the need for new infrastructure and marketing.[6,148,149]

Pollution prevention

Pollution can be prevented through several mechanisms. For instance, vegetation buffer strips can be created between fields and freshwater habitats to reduce the volume of fertilisers entering the habitats.[150] Farmers who apply for the Sustainable Farming Incentive (SFI) can opt to be paid £451 per hectare each year to establish and maintain buffer strips.[151]

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[m] Plasma is ionised gas.[143]

[n] Struvite is comprised of magnesium ammonium phosphate. [147]

Research has also shown that other approaches such as biochar can reduce the amount of nutrients leaching from the soil into the surrounding environment.[152] Additionally, some of research indicates biochar improves nutrient availability.[153,154]

An alternative approach to incentivising water pollution management is net nutrient neutrality[o] markets. Natural England has recently announced a scheme where 'nutrient credits' can be sold to housing developers that fund mitigation activities in the Tees area.[156,157] The credits are generated by landowners adopting measures to prevent water pollution from fertiliser use.

The Solent Catchment Market has designed a trading platform where developers can bid for nitrogen and phosphorus mitigation credits from verified nature-based projects, such as wetlands constructed to prevent transport of nutrients into freshwaters (PN 709).[158] The market operator, Entrade, is responsible for verifying the effectiveness of the projects.[159]

The viability of nutrient markets have been demonstrated.[160] For instance, a multi-country nutrient market for the Baltic sea delivered a reduction of nitrogen and phosphorus nutrient via a 'stacking' nutrient market.[p,161] However, some UK stakeholders have raised concerns about credit prices and confidence in the regulation of the market (CBP 9850).[163,164]

Such approaches can prevent water pollution, but different approaches would be required to address air pollution and soil health impacts. For instance, using nitrification inhibitors' (NIs), which reduces microbes' ability to carry out nitrification. This in turn reduces nitrogen losses, which can improve soil health and air quality.[165,166]

Replacing artificial fertilisers

Organic fertiliser

Organic fertilisers as described in Table 1 and 4, could provide an opportunity to diversify the UK's fertiliser use. Organic fertilisers can provide both macro and micronutrients to the soil, as well as improving soil texture, structure and increasing soils capacity to hold water and nutrients.[167] They provide long-term fertilisation of the soil.[168]

Studies suggest organic fertilisers have the potential to replace artificial fertilisers in some cases.[99] However, other experiments and farmer survey data suggest it is not possible for some farms to completely replace artificial fertilisers.[99,169,170]

Organic fertilisers vary greatly, and the nutrient content is less predictable than artificial fertilisers creating challenges for fully replacing artificial nutrient sources.[171,98,99] In addition, studies suggest the large volumes that could be needed may be

[o] Nutrient neutrality describes the process of offsetting pollution via mitigation.[155]

[p] Credit stacking markets allows for credits to be sold to separate nitrogen and phosphorus markets.[161,162]

impractical and expensive to transport long distances.[3,172] Some organic fertilisers, such as manure, can be concentrated to overcome this disadvantage.[173]

Additionally, several regulations and industry standards mean that most organic inputs except manures are required to undergo processing,[174–177] or require a long preparation and stabilisation process to achieve readiness.[177]

Table 4 Summary of organic fertilisers

Type	Definition
Livestock manures	Farmed animal waste products such as solid manure and slurry.[174] Livestock manures can be processed resulting in a more concentrated form, such as poultry and swine manure ashes.[178]
Biosolids	A derivative of treated sewage sludge.[171,179] Biosolids can decrease the demand for non-renewable phosphorus.[179]
Digestate	A product of anaerobic digestated organic matter (PN 387) which can be derived from manures or crops.[180,181]
Green manure	Green manures are plants used specifically for promoting soil fertility and improving the structure of the soil, such as legumes.[181,182]
Compost	A product of decomposed aerobic organic matter. Some examples of feedstock for compost may be green and food waste.[171,183]

Biofertilisers

A wide diversity of bacteria, fungi, and algae classified as biofertilisers naturally occur in the soil.[184] Biofertilisers can be divided into four main categories (Table 5).[184]

Biofertilisers increase crop capacity to access nutrients.[185] For instance, research has shown that biofertilisers can increase crop growth and yield by 10–40%.[184] Evidence suggests biofertilisers can also improve drought tolerance, plant health and salt tolerance.[29]

Whilst biofertilisers' reproducibility, shelf-life and storage requirements are barriers to some farmers using them, further investment may bring them up to a higher technological readiness level (PN 707).[186] However, commentators have raised the need for regulators to assess the impacts of introducing non-native soil microbiomes.[187]

Table 5 Summary of biofertilisers	
Term	**Definition**
Nitrogen-fixers	Plant root or free-living bacteria that transfer nitrogen from the atmosphere into ammonia.[188,189]
Potassium solubilisers	Potassium-solubilising microbes that release acids or biofilms that convert inaccessible potassium compounds into potassium that is accessible by the plants.[190]
Phosphorus solubilisers	Bacteria and fungi that secrete compounds that convert insoluble phosphorus into bioavailable phosphorus.[191]
Plant growth-promoting rhizobacteria (PGPR)[q]	Bacteria that produce compounds that support crop nitrogen fixation and stress tolerance.[193]

More efficient use of artificial fertiliser

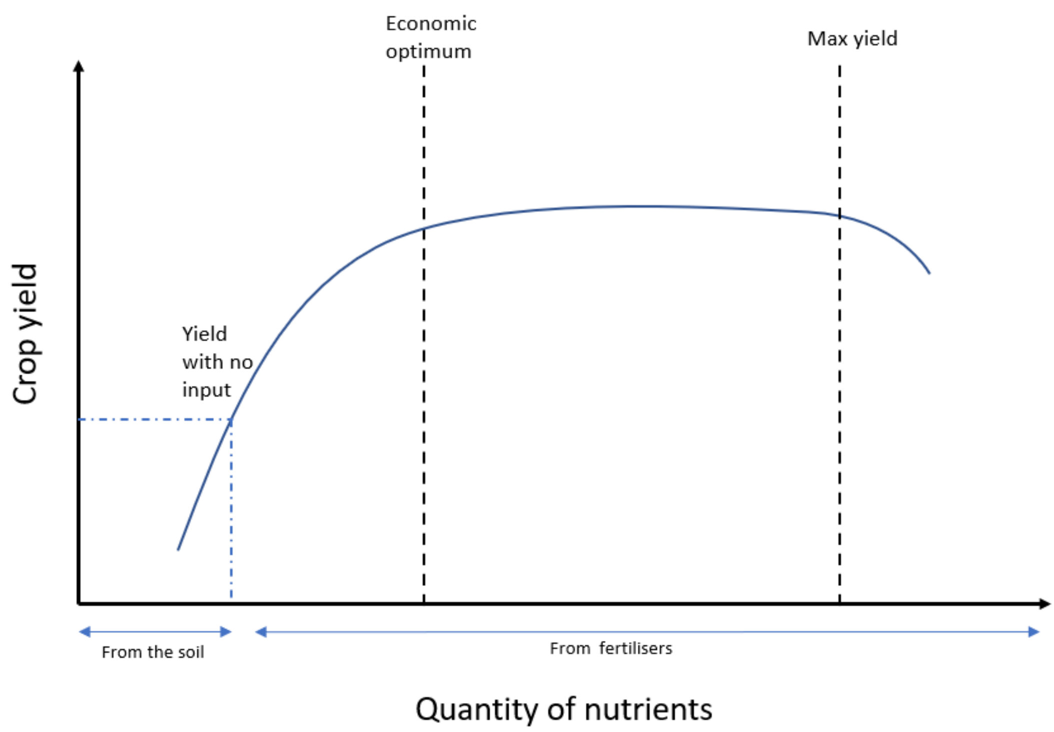
As the amount of fertiliser increases so does the yield of the crop, but only up to a certain point.[194] Beyond that point there is no benefit from adding additional fertiliser (Figure 2).

It has been estimated that £397 million of artificial fertiliser is wasted each year in the UK due to over-application.[195] Research by the Agriculture and Horticulture Development Board suggests that UK farmers could potentially reduce up to 50% of the nitrogen fertilisers on specific crops without seeing a significant reduction in yield.[196] Additionally, improved nutrient management planning can increase productivity.[197]

Denmark reduced both its nitrogen artificial fertilisers and manure usage between 1990-2011 through a series of policies in conjunction with monitoring and enforcement. Nitrogen artificial fertiliser was nearly halved and manure use reduced by approximately 7%. Despite this, Danish agricultural production between 1990-2011 remained relatively stable.[198]

[q] PGPR is the term to describe the bacteria that are situated in the rhizosphere segment of the soil that improve plant growth.[192]

Figure 2 Fertiliser application curve vs Plant yield



Source: Adapted from Small Farmers and Sustainable N and P Management: Implications and Potential Under Changing Climate[194]

Precision application

Precision agriculture has been proposed as a potential solution to over-application (PN 589, PN 505).[199] An array of technologies can be used to map, monitor and manage the nutrients in the soil. For example, variable rate application technology (VRT) considers different soil types and conditions,[200] then uses spatial information to modify the rate of application of fertiliser within fields.[201] Previous assessments of VRT has shown more than a 60% reduction in fertiliser use and more than 7% cost reduction on farms in Greece.[202]

Improving uptake efficiency of the crops

A significant amount of fertiliser is not used by the crop. Some research indicates that between 40–70%, 80–90% and 50–70% of nitrogen, phosphorus and potassium fertilisers, respectively, is lost to the environment.[203] Other research indicates a broader range of 20–80% of the nutrients within fertilisers are lost to the environment,[204] highlighting the importance of nutrient management planning.[181]

Research measuring the uptake efficiency of crops, found typically 30–40% of nutrients are used by the crop.[28] However, phosphorus has been particularly identified as having comparably lower crop availability,[204]with uptake efficiency at between 10-15% for phosphorus fertilisers[205] (PN 477). Phosphorus may be recovered by subsequent crops but this requires good nutrient management planning to maintain the levels of phosphorus within field soils.[204,205] Similarly, some micronutrients may have lower crop availability and uptake efficiency.[204]

There has been significant research into ways to increase crop uptake efficiency, for instance, by selective breeding or genetic editing (GE). However, there are challenges such as legal restrictions to GE in some countries of the UK (PN 663, PB 50).[206,207]

Alternatively, fertilisers can be modified to release nutrients more slowly to ensure better uptake by the plant. Nanofertilisers[r] are being developed that may make this more efficient than conventional controlled-release fertiliser.[203,210]

Improving soil health

Soil management practices help to improve soil health, but vary in effectiveness between soil types (PN 502). Practices include intercropping, reducing tillage, increasing crop rotation, introducing cover crops,[s] and other organic materials.[63]

Improved soil health results in better water storage within the soil and increases the recycling of organic matter and nutrients in the soil. [212] This in turn increases the nutrient efficiency of both organic and artificial fertilisers,[213] and reduces the amount of fertiliser required.

However, some of these practices might not be viable for some farmers due to the economic costs of additional machinery, and the need for soil health management skills.[63,214,215] In addition, some of these practices may cause other unwanted effects. Recent research shows that in unploughed land the changes in the pore size in the soil could result in more leakage of chemicals applied to the field.[216]

The future of fertilisers

Generally, stakeholders agree that diversification and innovation of fertilisers and farming practices is required to maintain high food production and to reduce environmental impact (Figure 3).

There is a consensus among commentators that there is no one solution and the challenges require a systems approach, integrating different approaches to avoid unintended outcomes. Some argue that a one-health approach[t] (PN 701) could also facilitate this integration. The four main challenges to achieve diversification and innovation are set out in Table 6 below.

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[r] Nanofertilisers provides the nutrients required by the plant via nanoparticles. Nanofertilisers are typically encased inside a thin protective nanomaterial and are considers an emerging technology by researchers.[208,209]

[s] Cover crops are plants that are added to the field to improve soil fertility, they are grown alongside the primary crop but are not harvested.[211] Some example are clover and vetch (PN 502).

[t] The one-health approach is defined as "an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent." by the One Health High Level Expert Panel.[217]

Figure 3 A summary of the solutions for reducing fertiliser impacts

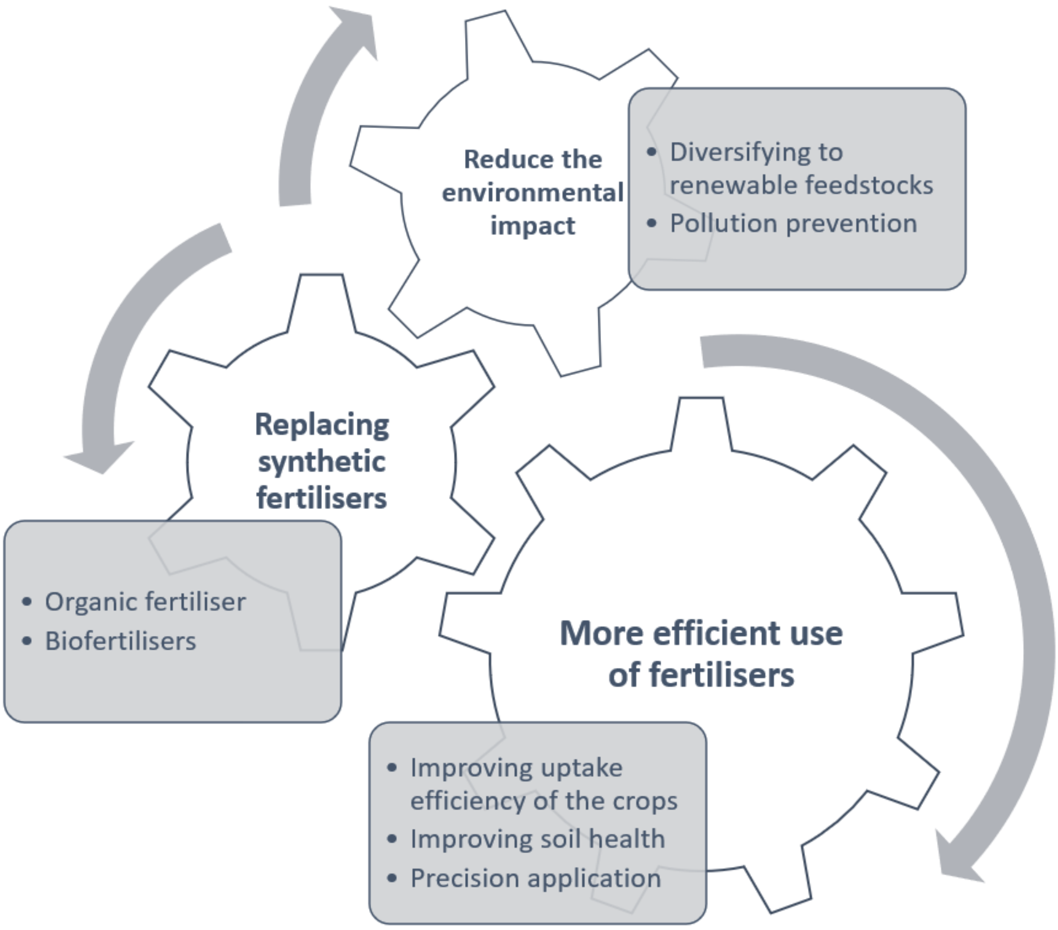

Table 6 A summary of the key challenges for diversification and innovation

Challenges	Description
Lack of investment in diversification and innovation	Farmers can be risk averse to adopting new techniques and technologies that may lead to crop failure or loss of yields and productivity (PB 51),[218,219] due in part to demands from other actors in the food supply chain (CDP 0147).[220] More investment may also be required to bring some technologies to readiness (PN 707).[221]
Insufficient evidence base	Knowledge exchange programmes and demonstration farms provide evidence in the form of case studies and transfer knowledge to farmers.[222,223–225] There is growing data on subfield soil nutrients, yet a lack of comparable data and long-term studies.[226,227] There is also insufficient research into agroecological practices with fewer inputs (PB 42).[228]
Need for cooperation across the UK	In England, livestock production and manure are mainly in the west, whereas crop production is in the east.[229] Additionally, the impact of fertilisers is not localised. Catchments are shared between farmers and some between UK nations. Nitrates can also be transferred regionally and nationally by air pollution. Such challenges require institutions or frameworks at relevant scales to coordinate management.
Ensuring a just transition	Policies seeking to reduce the environmental impacts of fertilisers may raise 'just transition' challenges for stakeholder groups,[40] such as farmers,[u] consumers affected by higher food costs or those groups affected by the impacts such as poor air quality, which can influence whether desired policy outcomes will be realised (PN 706).

[u] The important of a just transition process has been illustrated in the Netherlands where changes to nitrogen pollution legalisation led to 'stikstofcrisis' also known as 'the nitrogen crisis' which resulted in the closure of thousands of farms.[230]

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